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The Microphysics of Ice Clouds - A Survey

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AIR FORCE SYSTEMS COMMAND, USAF

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FOR THE COMMANDER

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Chief Scientist

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Published results of observations of crystal habits, particle sizes and numbers of ice particles in clouds are summarized and discussed. There are systematic variations with cloud type, and in some instances, with cloud age and location within a cloud system. However, the body of data available is insufficient to formulate a climatology of ice cloud microphysics. The several measurement techniques in current use are evaluated, as are some of the techniques now under consideration for future use. The particle enhancement

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20. Abstract (Continued)

observed on some occasions is discussed, and the various theories accounting for it presented. Finally, recommendations are made concerning future field programs and theoretical studies required before accurate predictions of the ice cloud microphysical environment can be made.

Preface

The thanks of the authors are due to Mr. D. McLeod, who reviewed some of the literature pertaining to techniques for measuring cloud particles; to Captain I. Cohen, who summarized several publications on the subject of ice particle enhancement, and also helped prepare the manuscript for publication; and to Mrs. P. Sheehy, who typed the many versions of the manuscript.

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1. INTRODUCTION

The systematic study of ice particles in clouds dates from the publication of Tor Bergeron's classic paper, in which he postulated that the presence of ice is a necessary condition for the formation of precipitation from clouds.[1] Although we now know that Bergeron's thesis was overstated, and that precipitation can grow from purely water clouds, the immediate effect of his paper was a surge of interest in the formation and growth of ice crystals. Laboratory experiments, supplemented by occasional aircraft observations, opened up an entirely new area of cloud physics, and established the framework for all later investigations into the microphysics of clouds and the processes by which precipitation is formed.

Many investigators felt that hygroscopic nuclei were required for the formation of ice crystals. The hygroscope properties of particles found in the atmosphere were investigated in the laboratory under various conditions of pressure, humidity and temperature. Free atmospheric measurements of ice-forming nuclei were made as functions of height, geographic location and air mass characteristics. The correlation of the concentration of ice-forming nuclei and the concentrations of ice crystals was far from perfect and left many unanswered questions.

(Received for publication 4 May 1979)

1. Bergeron, T. (1935) On the physics of cloud and precipitation, Proc. 5th Assembly UGGI, Lisbon 2:156.

For this reason a number of different theories on the formation and growth of ice crystals by sublimation, collision and accretion were formulated and to some extent tested in cloud chambers. Computations were made depicting the probable interaction of ice crystals in typical cloud structures, and a semiquantitative description of the growth of precipitation by the Bergeron process was evolved. These studies formed the basis for pioneer weather modification programs in the late 1940's and 1950's. Indeed, the desire to control the weather was the chief motivation for cloud physics research at that time.

Although the study of the ice phase in clouds is still of interest in explaining the physical processes leading to the formation of precipitation and therefore directly related to weather modification programs, new applications have now redirected the types of measurements and the course of research being pursued by the Air Force in the field of cloud physics. Some of these applications have immediate use and some are developing in parallel with new technologies and weapon systems.

Hypersonic vehicles experience weather erosion on leading surfaces while penetrating clouds containing ice, snow and rain. Measurements and predictions of ice/water content values, ice crystal types and size distributions are required. Premature transition from laminar to turbulent flow around a vehicle can be caused by ice particles surviving transition through the shock wave and roughening the surface. Size distributions under low concentration conditions are needed.

Microwave communications using ever shorter wavelengths and ever increasing path lengths, are severely affected by clouds, particularly those containing ice particles. In order to estimate their effect, one must know the concentrations, dimensions, shapes and orientation of the particles along the transmission path. The effectiveness of microwave transmission of energy or as a weapon system is dependent on the loss of power due to attenuation and scattering of the beam by clouds and precipitation.

Moving from the microwaves into the shorter wavelengths in the electromagnetic spectrum, the cloud and precipitation particles become large with respect to the wavelength and the interactions become much more complex. Long microwaves and most hydrometeor regimes interact in the manner described by Lord Rayleigh. The shorter microwaves require the use of Mie theory, but neither theory can handle the bright band or melting level in the atmosphere.

Below the microwave region lies the visible part of the electromagnetic spectrum where classical optical ray tracing satisfactorily explains such phenomena as rainbows, haloes, and sun dogs. On the other hand, the attenuation of light becomes much more complex because of the interaction with air molecules. Laser communication and weapon systems are severely restricted by intervening clouds. Cirrus clouds are of special interest because of their widespread

occurrence and because so little is known about their density, composition and particle size distributions.

While still considering the visible part of the electromagnetic spectrum, one should mention the role of clouds in reducing the efficiency of solar collectors. Many solar collectors depend on direct sunlight that can be focused for increased efficiency. On overcast days the sun's rays are scattered by the clouds. A large part of the energy is reflected or scattered back into space from the clouds, but some of it is scattered through the clouds and reaches the collector. However, because of the angle of arrival, the light is not focused and the efficiency is significantly reduced. Those collectors which do not depend on concentration of the direct solar rays just do not receive and convert enough solar energy to be useful on cloudy days. There is evidence in the variations noted in efficiency curves of solar collections that the attenuation of solar energy by thin, "invisible" cirrus should be taken into account for design purposes. This means that the density and occurrence of cirrus clouds must be determined on a new and better basis.

Another application of ice cloud microphysical data is in the evaluation of a laminar flow wing being considered by the National Aeronautics and Space Administration for use on a future transport aircraft. This wing is expected to reduce the drag (and hence, increase the aircraft's range) as much as 30 percent, compared with a conventional wing. The decrease in drag is achieved by drawing air in through narrow slots so that the flow over the wing remains laminar, rather than becoming turbulent, as it does over present wings. Experiments with the concept, conducted by Northrup Aviation on the X-21 in 1964, indicated that ice particles above a critical size interfered with the laminar flow by blocking the narrow slots. This loss of laminar flow sometimes occurred outside of opaque clouds, in areas of good visibility. In order to determine the usefulness of laminar flow wings, it will be necessary to calculate the probability density function of various particle size distributions in non-opaque ice clouds.

Two other aspects of Air Force cloud physics research intimately intertwined with the microphysics of ice clouds are: (1) aircraft icing and (2) the microphysics of the melting layer. Icing occurs in supercooled clouds or in layers of cold air that underlie layers of warm air. In the latter case, the precipitation falling out of the warm layer formed higher in the atmosphere as ice or snow; hence understanding of these layers is important. Moreover, the melting level is important for a number of reasons. Among these are: (1) The top of this layer usually contains the highest liquid water content because the large snow aggregates have slower fall speeds than either the crystals above them, or the rain below. A cold airplane descending through this region can accumulate significant amounts of ice. (2) Electrical activities seem to concentrate in this region. For the radar meteorologist, the bright band has remained an enigma

because the large snow aggregates melt from the outside towards the center; hence they present a large wet surface to the radar. The radar interprets these as large drops; this is depicted as the bright band on the radar screen. This means that at present the bright band returns cannot be used quantitatively by the radar meteorologist to interpret the physical parameters of the precipitation. Knowledge of the structure and formation of the snow above the bright band would facilitate the interpretation of the melting of snow and of the structure of the bright band.

In the last few years it has been found that the occurrence of high thin cirrus clouds is much more prevalent than previously thought. Even though some have suggested that this is due to the increase in jet aircraft traffic at altitudes between 10 and 14 km, it is our opinion that this thin or "invisible" cirrus always has been present but it has not been adequately or properly observed simply because of the lack of requirement for such information.

2. MEASUREMENT TECHNIQUES

2.1 Measurement of Ice Nuclei Concentrations

From theory and observation, it is known that concentrations of ice crystals in clouds range from 0.1 per liter to approximately 1000 per liter (four orders of magnitude). Assuming a one-to-one relation between ice crystal concentration and ice nuclei concentration, one observes that nuclei counting devices must have sampling volumes not less than 10 liters, and be capable of measuring concentrations of up to 1000 per liter. For a 10-liter volume, this corresponds to counts between 1 and 10,000.

All ice nuclei counters use one of seven techniques for detecting the presence of ice nuclei. In the mixing chamber, warm moist air is introduced into a cold chamber. This produces supersaturation over ice and a slight subsaturation over water. The active ice nuclei present then form ice crystals. In the expansion chamber, air is expanded and cooled at different rates to simulate updrafts in the atmosphere. A major limitation of this technique is the lower than true count, caused by the deposition of nuclei on the wall of the chamber. To eliminate this problem, the rapid expansion chamber expands and cools the air at rates much higher than those encountered in the atmosphere. However, the shorter observation time causes other problems in interpreting results.

Instruments that require the settling of supercooled water droplets through the volume of air to be measured, prior to the counting of drops frozen, have a disadvantage in requiring large concentrations of nuclei before they are effective. Thermal diffusion chambers are effective instruments for measuring condensation nuclei.

When used to measure ice nuclei concentrations, these chambers have the disadvantage of not being able to sample the large volumes required to detect low concentrations. An improvement is the use of Millipore filters as a collection device for the diffusion chamber. The allowable sampling time is longer, and the sampling size correspondingly larger (up to 2000 liters). Finally, simple droplet freezing on treated slides can be used to measure the nuclei concentration, under the assumption that each nucleus resulted in a frozen droplet. Analysis of the results is tedious, and there may be loss of drops between sampling and counting. Hence, this method may produce artificially low results.

A summary of the various techniques for measuring ice nuclei concentrations is given in Table 1.[2] A discussion of this subject can be found in Mason.[3] In particular, all techniques for measuring ice nuclei concentration have a fundamental uncertainty when attempts are made to interpret the results in terms of observed ice particle concentrations. Because it is impossible to reproduce the actual slow cooling and prolonged supersaturations found in the free atmosphere, the measured ice nuclei may be activated in the laboratory at different temperatures and in different ways (sublimation, freezing, accretion) than they would in actual clouds. This must be borne in mind when discussing the discrepancies between observed ice particle concentrations and ice nuclei concentrations.

2.2 Measurement of Ice Particle Concentrations

It is no longer sufficient to measure simply the concentration of ice particles in different cloud systems, though this information is still necessary. Current users require observations of crystal types and dimensions, and their correlation with cloud types and locations. Measurement devices fall into two categories: those which require capture of the particles (for example, the Formvar replicator, the foil sampler, cat's fur, soot or silicon coated slides, and snow stick); and the remote sensing devices (such as shadowgraphs, photography, scatter probes, microwave cavities and charge transfer devices). Each of these has its limitations. Data collected with the Formvar replicator (Figure 1) may underestimate the size because of fragmentation of the crystals on impact (Figure 2). The foil sampler[4] misses most particles smaller than 1 mm in maximum dimension since the groves in the backing plate are generally not less than 250 μm apart (Figure 3). Cat's

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2. Hallett, J. (1972) Influence of cloud dynamics on the relationship between ice nucleus measurement and ice crystal concentration, J. Rech. Atmos. 6:213-221.

3. Mason, B.J. (1971) Physics of Clouds, Clarendon Press, Oxford.

4. Church, J.F., Pocs, K.K., and Spatola, A.A. (1975) The Continuous Aluminum-foil Sample: Design, Operation, Data Analysis Procedures, and Operating Instructions, AFCRL-TR-75-0370, AD A019 630.

Table 1. Characteristics of Ice Nuclei Detection Systems

Instrument	Sensitive Time	Saturation Ratio	Most Likely Process	Limitations
Mixing	10^2 sec	Just less than water saturation	Deposition Contact nucleation	Mixing leads to local supersaturation fluctuations; supersaturation not controlled.
Expansion (slow)	Variable, to 10^3 sec	Water saturation	Drop freezing	Wall effects - loss of water vapor, nuclei.
Expansion (rapid)	0.1 sec	Variable	Deposition Contact nucleation Drop freezing	Soluble particles fail to dissolve. Insufficient time for surface processes to equilibrate. Insufficient time for Brownian capture of small particles.
Settling	10 sec	Water saturation	Contact nucleation	Large nuclei concentration required.
Diffusion	10^2 sec	Variable	Deposition Contact nucleation Drop freezing	Size — large air volumes cannot be examined continuously to monitor low concentrations. Particles lost by fallout and diffusion.
Diffusion with millipore	10^4 sec	Ice to slight water supersaturation	Deposition Drop freezing	Sample contamination with Aitken nuclei, surface removal of vapor at water supersaturation.
Drop freezing	Variable			Dissolution and coagulation during storage.

[After Hallett (1972)]

fur or silicon coated slides may be used to capture the snow or ice particles for inspection if on the ground, provided the aircraft is flying at low air speeds or provided a decelerator is mounted on the aircraft. A snow stick with a calibrated area exposed perpendicular to the airflow and visible from inside the aircraft provides real-time information on crystal type, particle size and concentrations. Normally the lower limit of useful data are 200 μm, but smaller particles may be observed in detail by drawing the cold-soaked snow stick inside the aircraft and viewing with a calibrated eyepiece.

All of the remote sensors suffer from uncertainties in the interpretation of data. The laser scanning devices designed by Knollenberg[5, 6, 7*] have a very important advantage in that they permit the automatic reduction of data. This

*See References, page 33.

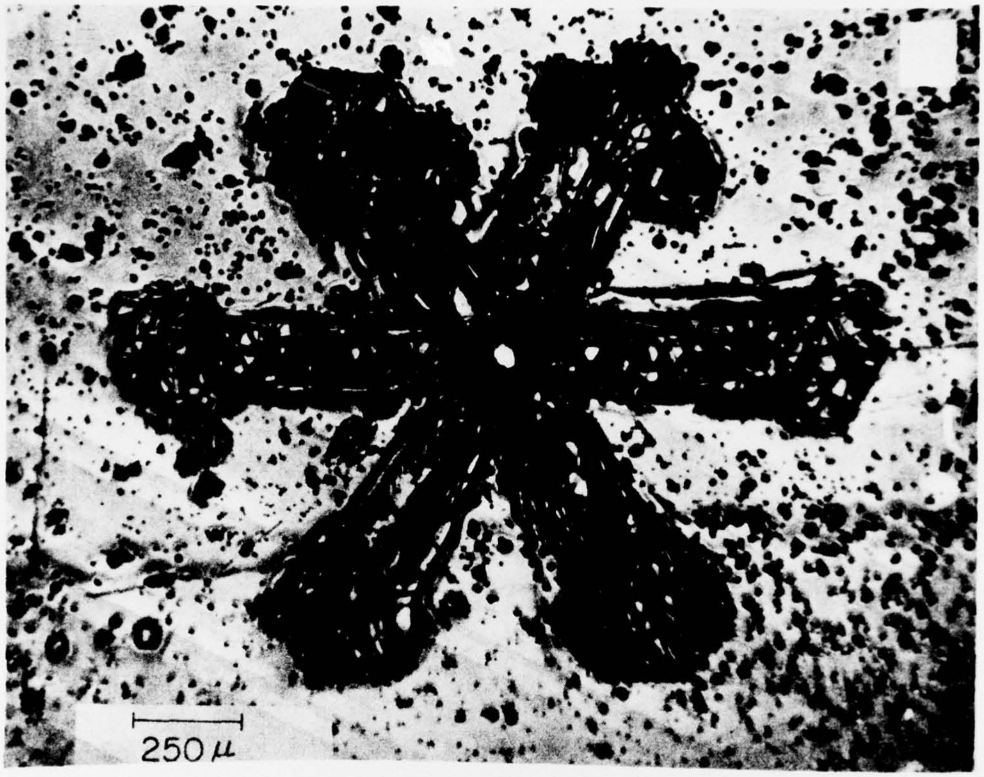


Figure 1. Ice Crystals Collected with Formvar Replicator. This unique replica of a rimed dendrite was obtained after searching hundreds of hours through replicator film

feature is essential for the compilation of any extensive statistics or climatology of ice cloud microphysics.

The Knollenberg devices [produced by Particle Measuring Systems, Inc. (PMS)] and their calibration are described extensively in the literature by Knollenberg,[5, 6, 7] and by Heymsfield and Knollenberg,[8] Heymsfield,[9] and Cunningham.[10] Briefly, the system consists of a laser beam illuminating a line

8. Heymsfield, A.J. and Knollenberg, R.G. (1972) Properties of cirrus generating cells, J. Atmos. Sci. 29:1358-1366.

9. Heymsfield, A.J. (1976) Utilization of aircraft size spectra measurements and simultaneous Doppler radar measurements to determine the physical structure of clouds, J. Atmos. Sci. 29:1358-1366.

10. Cunningham, R.M. (1978) Analysis of particle spectra data for optical array (PMS) 1D and 2D sensors, Preprints, 4th Symposium on Meteorol. Observations, pp. 345-350.

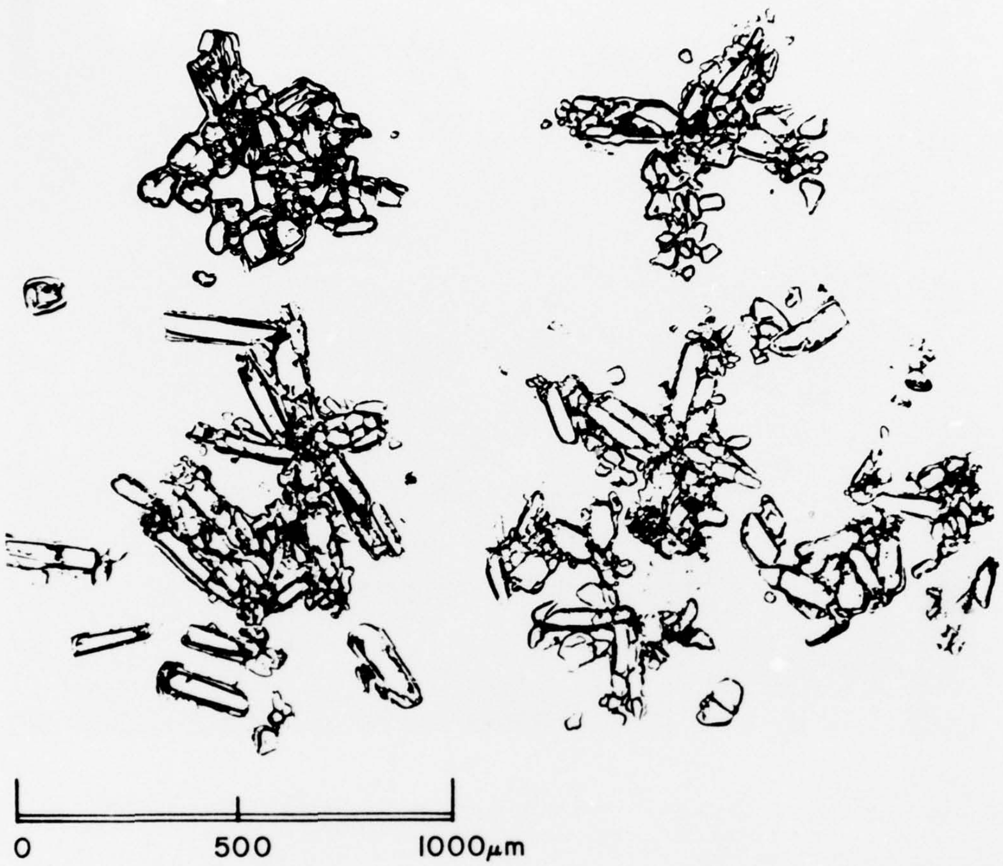
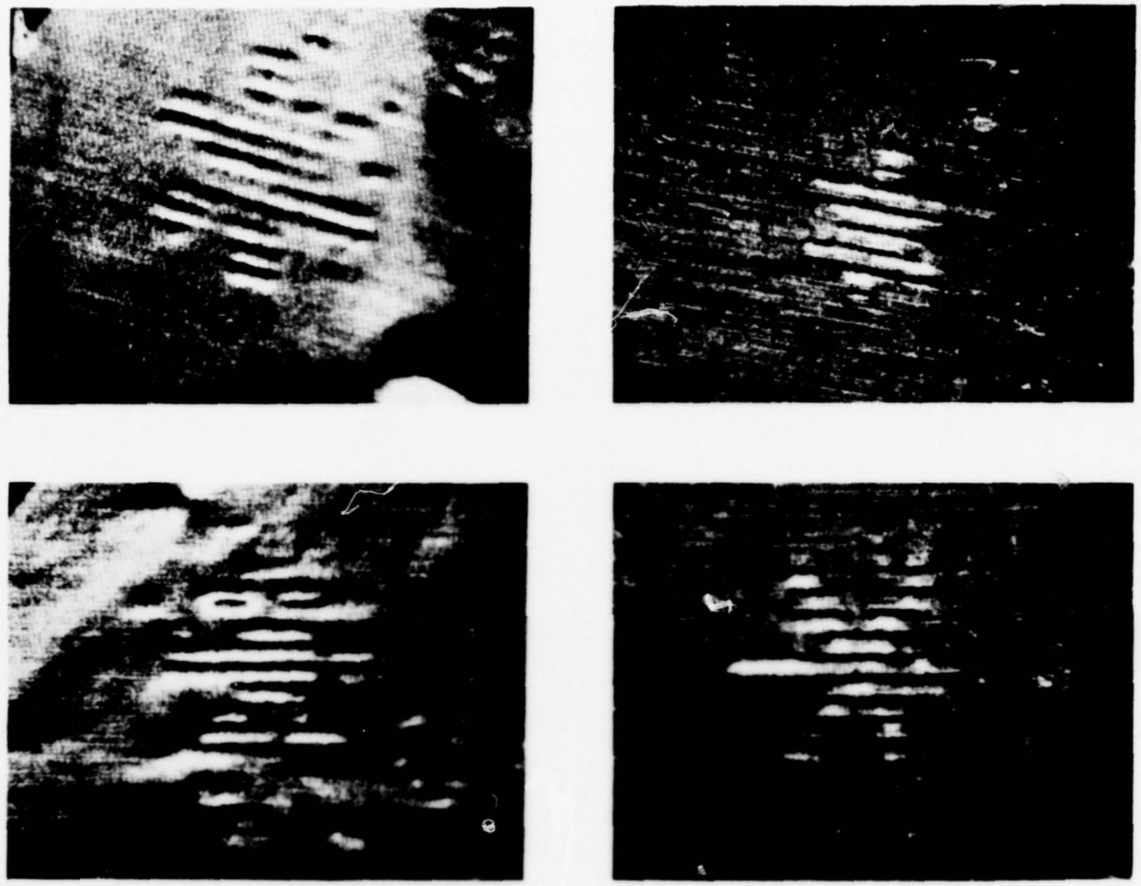


Figure 2. Ice Crystals in Cirrus Clouds, Showing Fragmentation on Impact. This was taken at a time when a 22° halo and other optical phenomena were observed

of photodiodes. As a particle falls through the viewing volume, it occludes some of the diodes, the number and location of which are determined by the particle's size and shape. In the one-dimensional (1-D) instruments, the maximum number of diodes occluded during the passage of a particle through the sample volume is recorded as the particle size. In the two-dimensional (2-D) instruments, a rapid scanning system records the diodes occluded per unit forward motion of the aircraft. This forward motion equals the minimum grid size, and hence the smallest sized particle measurable by the device (25 μm for the cloud probe, 200 μm for the precipitation probe). Figure 4 is an unusually clear example of dendrites recorded by the PMS 2-D precipitation probe. If a particle is only partially



Aluminum foil impacts, magnified 15 times, from stellar crystals at 10K ft.

Figure 3. Ice Particle Samples Obtained With Aluminum Foil. Impacts of stellar crystals. Ribs behind the soft foil are 250 μm apart

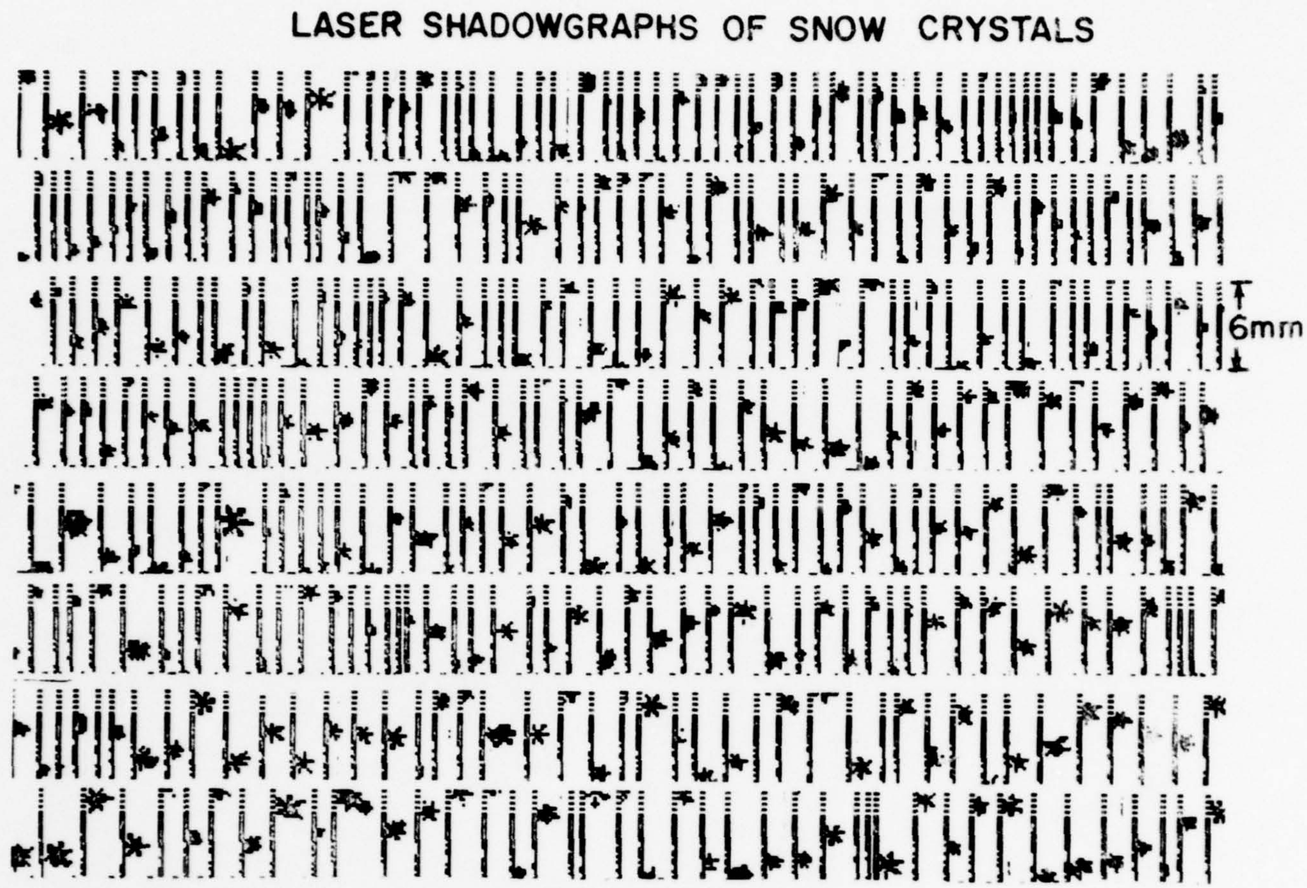


Figure 4. Dendritic Crystals Recorded by the PMS 2-D Precipitation Probe

contained in the 1-D sampling volume, it is rejected. Since the volume reflected by this edge reject feature is larger for larger size particles, the effective 1-D sampling volume for larger size particles is reduced. For the PMS 2-D instruments, estimates of missing parts of the particles may be made, but the design of the computer programs and the interpretation of results is still subjective.

The PMS scatter probes are calibrated only for small spherical water drops, and are based on the principle that the intensity of light scattered from spherical water drops is proportional to the drop size. Scattering from ice particles is heavily dependent on crystal shape and orientation; hence the use of scattering intensities to determine size or mass of an ice particle is merely wishful thinking. Factors not yet evaluated are the near sphericity of the smaller particles and nonlinear interaction of the light waves with the small features of the ice particles. On the other hand, the PMS scatter probe is the only instrument operating in the small size range which provides large amounts of size data for statistical purposes.

Efforts in the past to utilize photographs[11] or holograms[12] of ice crystals have encountered data reduction problems and wave-optics effects for the smaller crystals. Some progress is being made in automating the reduction of holograph data. However, analysis time remains a major drawback to the use of photographic or holographic data.

The use of microwave cavities for detection of the mass of particles has been suggested, as well as the measurement of residual charges left by ice crystals hitting a plate on the aircraft. Neither of these looks as promising as those techniques already in use.

3. TYPES OF ICE CRYSTALS IN CLOUDS

The most extensive classification of naturally occurring snow crystals is that of Magono and Lee.[13] Their work, a modification of that of Nakaya,[14, 15] lists a total of 80 crystal types, including irregular shapes and combinations of shapes. Figure 5 gives the environment (temperature and vapor supply) producing 27

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11. Cannon, T.W. (1975) Photographic techniques for measurements of atmospheric particles in situ from aircraft, J. Appl. Meteorol. 14:1383-1388.

12. Thompson, B.J. (1974) Holographic particle sizing techniques, J. Phys. E. Sci. Instrum. 7:781-788.

13. Magono, C. and Lee, C. (1966) Meteorological classification of natural snow crystals, J. Fac. Sci. Hokkaido Univ., Ser. VII, 2:321-335.

14. Nakaya, U. (1951) The formation of ice crystals, Compendium of Meteorology; Am. Meteorol. Sci., 207-220.

15. Nakaya, U. (1954) Snow Crystals, Harvard University Press.

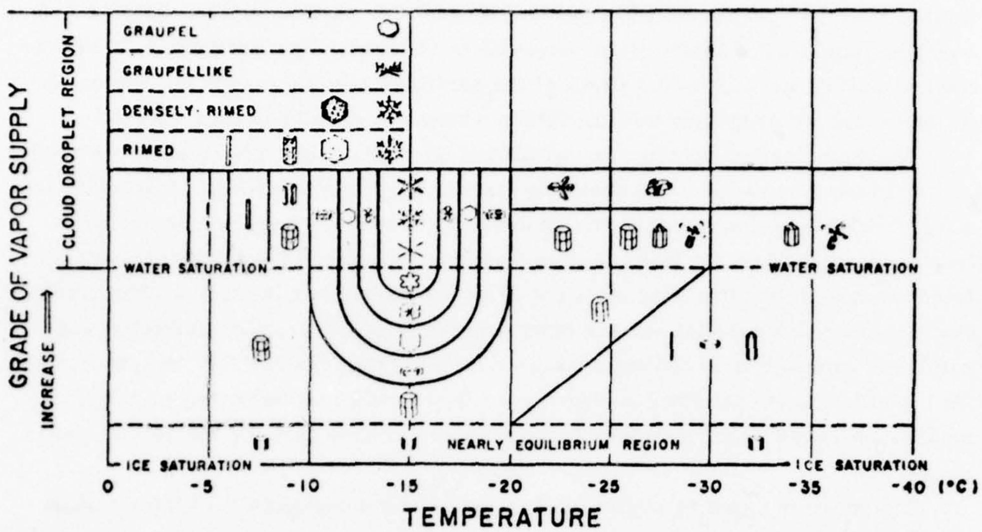

Figure 5. Temperature and Humidity Conditions for the Growth of Natural Snow Crystals of Various Types [After Magono and Lee (1966)]

representative basic crystal types. The meaning of the symbols used in the illustrations are listed in Table 2.

Observations in clouds often indicate the presence of several crystal types at any given altitude. This led to a suggestion by Weickmann[16] that, by use of appropriate values of crystal growth and fall speeds, individual crystals could be traced to their generating layer, and the temperature and relative humidity of that layer deduced from the crystal shape. This was successfully done by Grunow[17] among others. Many later investigators were frustrated, however, by the high proportion of irregularly shaped particles they observed at each altitude.

A logical outgrowth of this result is the conclusion that the vertical distribution of crystal types throughout a cloud is to some extent a function of the age of the cloud. The older the cloud, the farther will the crystals have fallen, and the further along will they be on their growth curve. Fallout and evaporation will also have a greater effect on older clouds than on newly developed clouds. It may be possible in the future to set up a computer model that successfully predicts the crystal mixes found at different levels in a cloud at different times, and to take

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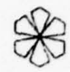
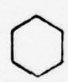
16. Weickmann, H.K. (1957) The snow crystal as an aerological sonde, Artificial Stimulation of Rain, Pergamon Press, 315-325.

17. Grunow, J. (1960) Snow crystal analysis as a method of indirect aerology, Physics of Precipitation, Am. Geophys. Union, 130-141.

Table 2. Standard Symbols for Crystal Types*

Form	Name	Form	Name	Form	Name
	Elementary sheath		Densely rimed stellar crystal		Crystal with sectorlike branches
	Side planes		Solid bullet		Crystal with broad branches
	Elementary needle		Hollow bullet		Stellar crystal
	Combination of side planes, bullets and columns		Solid column		Ordinary dendritic crystal
	Rimed needle crystal		Long solid column		Fernlike crystal
	Rimed columnar crystal		Hexagonal graupel		Thick plate of skelton form
	Rimed plate or sector		Hollow column		Scroll
	Rimed stellar crystal		Solid thick plate		Combination of bullets
	Densely rimed plate or sector		Hexagonal plate		Graupellike snow of hexagonal type

*The symbols shown here are used in Figure 5.

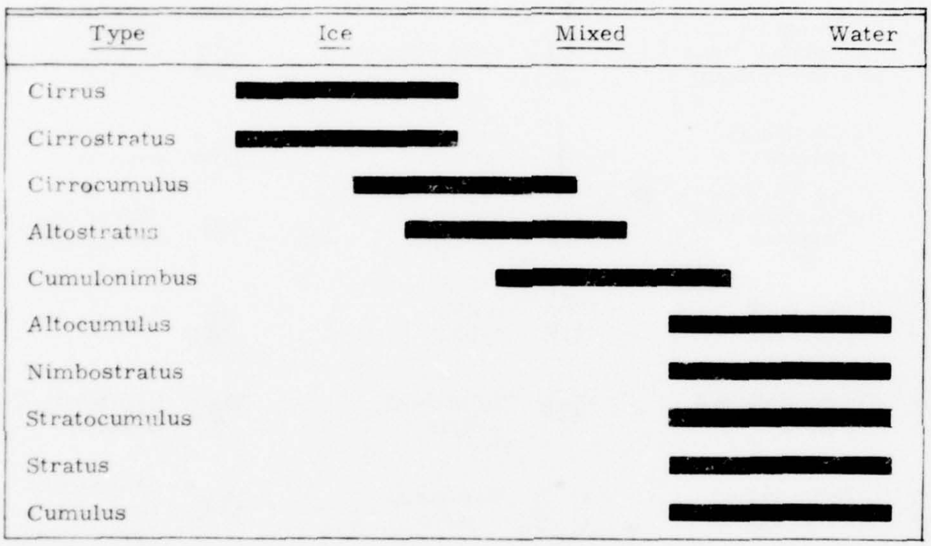
into account the interactions among the various crystal types, supersaturation and vapor supply.

4. ICE PARTICLE SIZES AND CONCENTRATIONS

The age of the cloud, in addition to affecting the crystal type, also has an effect on the sizes and concentrations of the particles. Some other factors affecting the microphysical properties of clouds are: cloud type; position within the storm system; geographic location; type of air mass; altitude; and vertical extent of the cloud. Published data generally consider only one or two of these variables, and it is not possible to ascribe the observed differences among the various measurements to any one of the unreported factors. The best that can be done at present is to give the range of reported values for each variable noted.

Of the ten cloud genera recognized by the World Meteorological Organization, only two (cirrus and cirrostratus) have been defined as always containing only ice crystals. However, all clouds may on occasion contain a mixture of ice crystals and water droplets, depending on their location and the season. In Table 3, cloud types are characterized qualitatively according to how often they are composed of water droplets, ice crystals, or a mixture of both.

Table 3. Composition of Clouds by Cloud Type Classification



Representative sizes and concentrations of ice particles in clouds are listed in Table 4 as a function of cloud type. There is also an observed dependence on age of the cloud, location within the cloud, and location of the cloud itself within the storm system. A few case studies demonstrating these dependencies have been published, but the body of data available is too scant to permit generalizations about the effect of these parameters on the ice particle concentration.

In their measurements in cirrus and cirrostratus clouds, Heymsfield and Knollenberg[8] found that the maximum ice water content (liquid water equivalent of the ice particles present) occurred just below the base of the generating cell. Approximately one-fourth of the particles were plates, with the remainder classified as bullets, columns, or bullet rosettes (combination of bullets). The spatial variations were more apparent than any variation with time.

Table 4. Representative Observations for Selected Cloud Types

Cloud type	Typical ice particle maximum dimensions	Typical concentration per meter^3	Typical liquid water content per meter^3	Location	Reference	Remarks
Cirrus	0.9 mm	3.5×10^4	0.20 g	Colorado, Minnesota	8	No geographic dependence LWC is ice water content
Cirrostratus	0.9 mm	2.2×10^4	0.15 g	Minnesota	8	Seeding effect on altocumulus below
Cumulonimbus	43 μm	10^6	1.0 g	Missouri	18	Ice all irregular shapes*
Stratocumulus	250 μm	160	0.05 g	Tasmania	19	Small rimed particles and columns
Stratus	14 μm	130	0.15 g	Arctic	20	No riming
Cumulus	35 μm	10^2 to 4×10^4	1.0 g	Florida	21	Water droplets more prevalent than ice. Ice was mostly graupel*
Altostratus$^+$						
Cirrocumulus$^+$						

*The classification of ice particles as "irregular" is subjective, and varies with observer.
$^+$No observations of purely altostratus or cirrocumulus clouds have been reported.

In contrast, observations in cumulus clouds by Hallett et al,[21] and in cumulonimbus by Koenig[18] both showed a definite change in the ice particle spectrum with time. In particular, young convective type clouds at sub-zero temperatures could be ice-free. Glaciation, once begun, proceeded rapidly. The variation with time was more pronounced than any variation with location within the cloud.

In their studies of Arctic stratus clouds, Jayaweera and Ohtake[20] found extremely low ice particle concentrations, compared with the concentrations found in similar types of ice clouds in the temperature zones.

Between 1969 and 1974, investigators at the University of Washington studied winter storms over the Cascade Mountains, in the Pacific Northwest. They found definite differences in crystal type, average size, and relative concentrations, depending on whether the clouds were pre-frontal, post-frontal or transitional.

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18. Koenig, L.R. (1963) The glaciating behavior of small cumulonimbus clouds, J. Atmos. Sci. 20:29-47.
19. Mossop, S.C., Ono, A., and Wishart, E.R. (1970) Ice particles in maritime clouds near Tasmania, Quart. J. Roy. Meteorol. Soc. 96:487-508.
20. Jayaweera, K.O.L.F. and Ohtake, T. (1973) Concentration of ice crystals in Arctic stratus clouds, J. Rech. Atmos. 7:199-207.
21. Hallett, J., Sax, R.I., Lamb, D., and Ramachandra Murty, A.S. (1978) Aircraft measurements of ice in Florida cumuli, Quart. J. Roy. Meteorol. Soc. 104:631-652.

Table 5. Summary of Microphysical and Synoptic Differences between Pre-frontal, Transitional, and Post-frontal Portions of Pacific Northwest Storms over the Cascade Mountains

Storm type	Clouds	Crystal types	Relative concentrations of ice particles (liter^{-1})
Pre-frontal	Layered from surface to 9 km with clear layers.	Often water saturated crystals at temperatures <-20°C (usually above 5.4 km); e.g., hollow bullets, side planes, hollow columns, radiating assemblage of plates, sectors and dendrites, also solid columns and solid bullets, combination of bullets. Usually sub-water saturaged at temperatures >-20°C (usually below about 5.4 km); e.g., plates, some crystals with broad branches and sector-like branches and warm region columns, thick plates.	Western slopes of Cascades: 100 to 1500. Eastern slopes of Cascades: 25 to 500. Puget Sound Basin: 50 to 1000.
Transitional	Layered to 5.4 km with embedded cumulus.	Water-saturated crystal type at all levels, e.g., hollow bullets, side planes, hollow columns, combinations of bullets, dendrites, stellars, some crystals with sector-like branches and broad branches only a few plates, many sheaths and needles, some warm columns.	Western slopes of Cascades: 0 to 10,000. Eastern slopes of Cascades: 0 to 1500. Puget Sound Basin: 0 to 5000.
Post-frontal	Convective with tops to 4.6 km.	Few crystals generally dendrites, a few plates and some needles and sheaths.	Western slopes of Cascades: 0 to 1000. Eastern slopes of Cascades: 0 to 100. Puget Sound Basin: 0 to 250.

[After Hobbs (1975)]

Table 5. Summary of Microphysical and Synoptic Differences between Pre-frontal, Transitional, and Post-frontal Portions of Pacific Northwest Storms over the Cascade Mountains (Continued)

Storm type	Relative concentrations of ice droplets (liter^{-1})	Liquid water content (g m^{-3})	Turbulence	Relative concentration of aggregated ice particles (liter^{-1})
Pre-frontal	Western slopes of Cascades: 250 to 10, 000. Eastern slopes of Cascades: 100 to 5000. Puget Sound Basin: 200 to 7500.	0 to 0.5. Some increase on wester slopes of Cascades. Liquid water concentration near zero for temperatures <-10°C (higher than about 4 km).	0 to light. Some increase on western slopes of Cascades.	10 to 100
Transitional	Western slopes of Cascades: 20, 000 to 350, 000. Eastern slopes of Cascades: 5, 000 to 80, 000. Puget Sound Basin: 10, 000 to 200, 000.	Up to about 5 km (about -20°C( ) 0.5 to 2.0.	Moderate to severe. Strong increase on western slopes of Cascades.	0 to 2000
Post-frontal	Western slopes: 35, 000 to 300, 000 (many small droplets, average 10 μm in diameter). Eastern slopes: 100 to 10, 000. Puget Sound Basin: 0 to 15, 000.	0.1 to 1.0	Moderate to severe. Strong increase on western slopes of Cascades.	0 to 10

[After Hobbs (1975)]

Table 5. Summary of Microphysical and Synoptic Differences between Pre-frontal, Transitional, and Post-frontal Portions of Pacific Northwest Storms over the Cascade Mountains (Continued)

Storm type	Riming	Precipitation rate (mm h^{-1})	Orographic effect of Cascade Mountains	Special features
Pre-frontal	Very little except near the surface in the Cascades. More riming over east slopes of Cascades than west.	Steady. 1.3 to 2.6	Increase in water saturated crystals such as dendrites, needles and sheaths. Increase in concentrations of aggregates on western slopes. Decrease in concentrations of ice crystals on the eastern slopes. Higher precipitation rate on western than eastern slopes.	Concentration of cloud particles quite uniform over large horizontal distances. Cold region crystals very common. Riming at low altitudes over Cascades and on eastern slopes.
Transitional	Quite common, particularly for warm region crystals; e.g., needles and sheaths.	Showery. Between 0 to 7.6	Heavy showers on western slopes often rapid clearing on eastern slopes. More riming on western than on eastern slopes, also more graupel and frozen drops on western slopes.	Graupel and frozen drops common. Concentration of crystals variable. Heavy riming, particularly on western slopes of Cascades near surface.
Post-frontal	Heavy riming on the few ice particles present.	Showery. Nearly 0 on eastern slope to 5.2 on western slopes.	Scattered heavy orographic showers on western slopes.	Graupel, aggregates and frozen droplets common particularly on western slopes of Cascades.

[After Hobbs (1975)]

Of course, the type of cloud also varies under these circumstances, and it may be argued that the observed differences might as easily be ascribed to cloud type as to position within a storm system, or age of the cloud.

The results of the University of Washington field program were reported by Hobbs,[22] and are summarized in Table 5.

A review at Air Force Geophysics Laboratory of a large amount of data taken with PMS 2-D probes (Figure 4) has shown that relatively more pristine crystals are found on the east side of the Rocky Mountains (in New Mexico, Colorado and Wyoming), than occur in the deep storm systems along the east coast of the United States.

5. RELATION BETWEEN ICE PARTICLE CONCENTRATION AND ICE NUCLEI CONCENTRATION

The measured concentrations of ice nuclei as a function of temperature in different parts of the world are shown by Bigg and Stevenson[23] (Figure 6). If a one-to-one relation exists between ice nuclei and ice particles, the measured concentrations of ice particles at various cloud temperatures will be of the same order of magnitude as the measured concentration of ice nuclei at that same temperature. The ice particle concentrations would tend to be less than the ice nuclei concentrations, because the efficiency of the nuclei would be less than one. One conclusion of Bigg and Stevenson was that, for the months studied (January, February, March), the temporal variations in nuclei concentrations at a given location were greater than any geographic variability.

Many observers have reported concentrations of ice particles that were orders of magnitude higher than the concentrations of ice nuclei at the pertinent temperatures. The mechanism by which ice particles multiply has been aptly characterized as "one of the outstanding problems in the microphysics of clouds."[24]

The high ice particle concentrations relative to ice nuclei concentrations occur in warmer clouds ($T > -12^{o}C$) and are generally cumulus, stratocumulus or numbostratus clouds. Arctic stratus, for example, do not show any multiplication of particles.

Typical values of the multiplication factor, or enhancement ratio, of ice particles relative to ice nuclei are shown in Figure 7. The fact that this ratio is

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22. Hobbs, P.V. (1975) The nature of winter clouds and precipitation in the Cascade Mountains and their modification by artificial seeding, Part I: natural conditions, J. Am. Meteorol. 14:783-804.

23. Bigg, E.K., and Stevenson, C. (1970) Comparison of concentrations of ice nuclei in different parts of the world, J. Rech. Atmos. 4:41-58.

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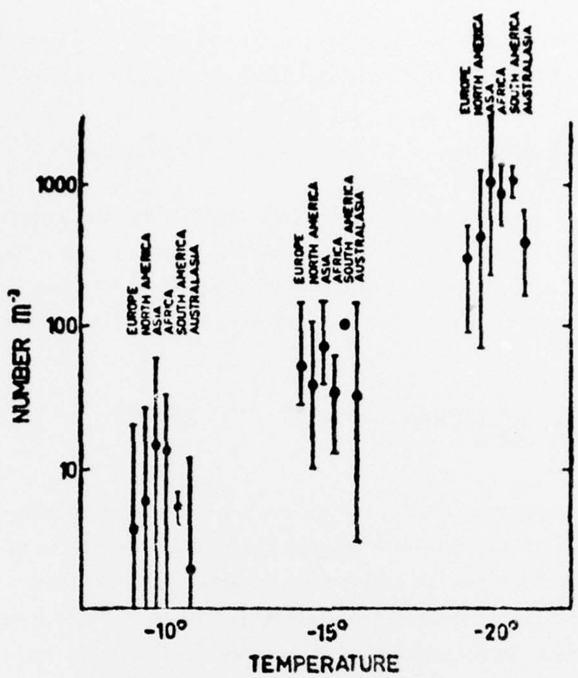

Figure 6. Range of Median Concentrations of Ice Nuclei in Different Geographical Groups, and Their Means [After Bigg and Stevenson (1970)]

higher at the higher temperatures, where the possible error in measuring ice nuclei concentrations is greatest, has led some observers (for example, Hallett[2]) to suggest that the fault is with the techniques for measuring ice nuclei concentrations. As discussed previously, all the measurement techniques listed in Table 1 have limited accuracies, especially at higher temperatures and/or low nuclei concentrations. Furthermore, it is impossible to reproduce the life histories of the nuclei, and determine their effectiveness, either in the cloud chamber or in the free atmosphere.

Nevertheless, there is sufficient duplication of these results, by many different observers using different instrumentation, to conclude that some sort of ice particle enhancement takes place in certain cloud types under certain circumstances. If prediction of cloud particle concentration is required, some knowledge of the enhancement mechanism involved is also necessary. It is this subject that has occasioned much debate, and concerning which further research is needed.

All the mechanisms of ice multiplication proposed involve the splintering of existing ice particles, with the splinters acting as ice nuclei, and a chain reaction causing a sudden, almost explosive, increase in particle concentration. In clouds

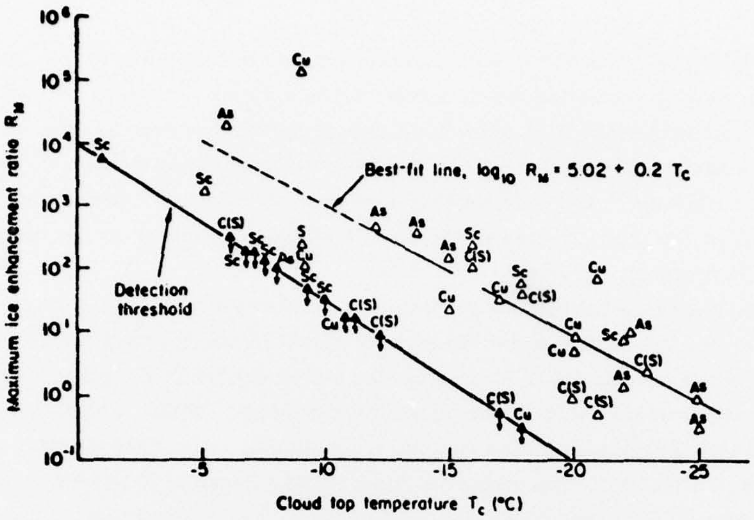

Figure 7. Ice Particle Enhancement Ratios in Different Cloud Types. Maximum ice enhancement ratios, R_M, for University of Washington flights in winters in 1971-72 and 1972-73. Values below the detection threshold are shown on the detection threshold line (solid triangles with an arrow attached). The best-fit line is to the measured values (open triangles) only. [After Hobbs and Atkinson (1976)]

in which particle multiplication is occurring, the measured concentration should be very dependent on age of the cloud. Although details differ, all the suggested causes of ice particle splintering can be assigned to one of four groups: freezing inwards at glaciation; freezing inwards during riming; shattering from internal pressure; and shattering as a result of collision between ice crystals.

If water drops freeze inwards at glaciation, there will be water trapped inside an outer shell of ice. When that internal water freezes, it will expand, causing the ice shell to crack and/or shatter. Several laboratory experiments (for example, Dye and Hobbs[26]) confirm this. However, additional laboratory experiments reproducing the conditions encountered in actual clouds indicate that very few, if any, ice particles are produced.[27]

Freezing inwards can also occur during riming, defined here as the freezing of a supercooled water drop by contact with an ice particle, as distinguished from freezing caused by ice nuclei alone. However, there is some discrepancy between laboratory results obtained by different investigators. Working in a cold room,

26. Dye, J.E. and Hobbs, P.V. (1968) The influence of environmental parameters on the freezing and fragmentation of suspended water drops, J. Am. Meteorol. 25:82.

27. Johnson, D.A. and Hallett, J. (1968) Freezing and shattering of supercooled water drops, Quant. J. Roy. Meteorol. Soc. 94:468-482.

Latham and Mason[28] extrapolated a splinter production rate of several hundred per second. Using a similar experimental arrangement, Aufdermaur and Johnson[29] concluded that it is rare for a freezing drop particle to eject an ice splinter. Aufdermaur and Johnson base their conclusions in part on the work of Johnson and Hallett,[27] and contend that a reinterpretation of Latham and Mason's data in light of the later studies of the nature of freezing water drops would resolve the discrepancy.

Another method whereby ice particles may multiply is the shattering of the ice particle (not the frozen water drop) as a result of the thermal shock the crystal receives when it collides with a supercooled water droplet. King and Fletcher[30] performed experiments with different size ice spheres, slabs, and thin discs. They found that actual shattering was rare, occurring only if the crystal was colder than -35°C. The time required for cracks to appear depended on the temperature of the crystal and (in the case of spheres) the crystal size. They concluded that thermal shock was not a likely mechanism for producing ice enhancement in the atmosphere.

Finally, collisions between ice crystals could result in their shattering. The efficiency of the mechanical splintering of ice crystals in the ice particles multiplication process was studied by Hobbs and Farber[31] in clouds over the Cascade Mountains in the State of Washington. They found this process could indeed account for the large number or ice particles in the clouds studied. Similar observations were reported by Grant[32] and Vardiman and Grant.[33] However, the verification is still indirect: The measurements produced no evidence that the mechanical shattering of ice crystals in collision with one another is not the cause of the observed crystal concentrations. However, there remains the necessity of measurements to demonstrate that this mechanism is indeed the one producing the observed particle enhancements.

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28. Latham, J., and Mason, B.J. (1961) Generation of electric charge associated with the formation of soft hail in thunderclouds, Proc. Roy. Soc. **260A**: 537-549.

29. Aufdermaur, A.N., and Johnson, D.A. (1972) Charge separation due to riming in an electric field, Quant. J. Roy. Meteorol. Soc. **98**:369-382.

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33. Vardiman, L., and Grant, L.O. (1972) A study of ice crystal concentrations in convective elements of winter orographic clouds, Preprints, 3rd Conf. of Weather Modification, 113-116.

6. EFFECT OF AGE AND LOCATION WITHIN A STORM

Several observers have documented the sometimes dramatic increase in ice particle concentration occurring over a short time interval during the growth stage of cumulus clouds (see, for example, Hallett et al[21] or Koenig[18]). Recently, Matejka et al[34] and Hobbs[22] have summarized the structure of the cloud systems associated with different types of frontal situations. Further research is needed to combine the effects of age of the cloud system and location within the system and produce an estimate of the ice particle spectra as a function of time and space. Work in this area is currently under way at AFGL.

Figures 8(a) through 8(d) are from Matejka et al, and indicate the regions within a cloud system where ice particles are found. This is in reality just another presentation of the information found in Table 5, with the very important addition of a representation of the spatial variations to be found within a system. Thus location, as well as time, is an important consideration in determining the microphysical environment.

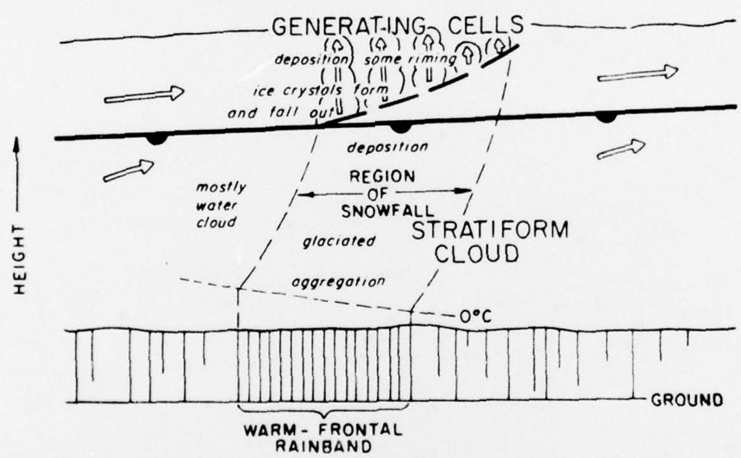

Figure 8a. Schematic Vertical Cross Section through the Clouds Associated with a Mesoscale Warm-Frontal Rainband. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below the cloud base represents precipitation; the density of the hatching corresponds to the precipitation rate. The heavy, broken line indicates the top of a mesoscale stable layer and the base of a mesoscale region of potential instability in which generating cells develop. Open arrows depict airflow and contrast the stable lifting within and above the warm-frontal zone with convective ascent in the generating cells. The motion of the rainband in the figure is from left to right [After Matejka, Houze and Hobbs (1978)]

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34. Matejka, T.J., Houze, R.A., and Hobbs, P.V. (1978) Microphysical and dynamical structure of mesoscale features in extratropical cyclones, Preprints, Conf. on Cloud Physics and Atmospheric Electricity, 292-298.

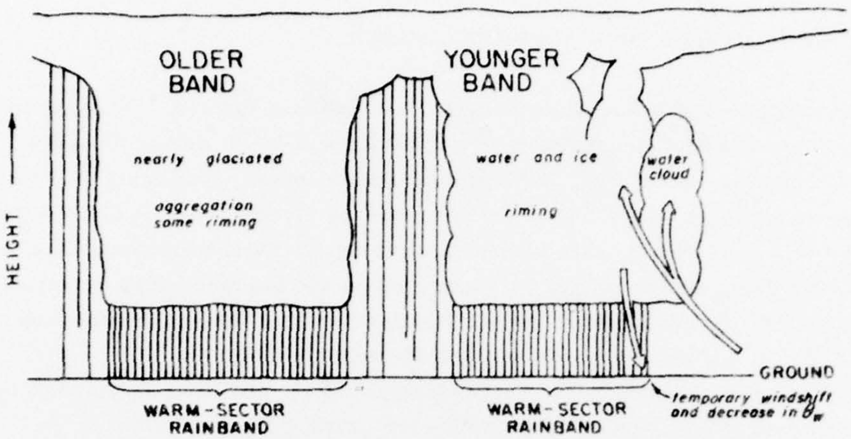

Figure 8b. Schematic Vertical Cross Section Through the Clouds Associated with Two Well-developed Warm-sector Rainbands. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict the updraft, in which air from the boundary layer feeds into the convection, and the downdraft accompanying the onset of precipitation from the bands. θ_ω is the wet-bulb potential temperature. The motion of the rainbands in the figure is from left to right [After Matejka, Houze, and Hobbs (1978)]

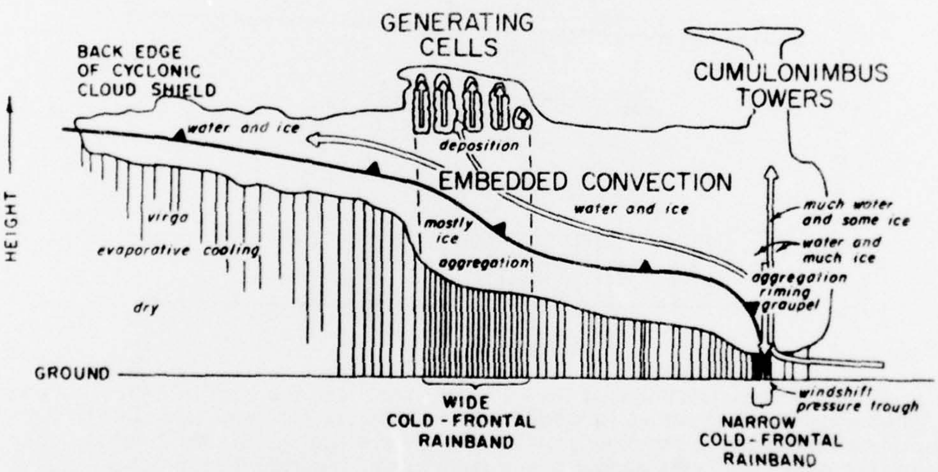

Figure 8c. Schematic Vertical Cross Section Through the Clouds Associated with a Cold Front, Showing Embedded Narrow and Wide Mesoscale Cold-frontal Rainbands. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict airflow relative to the front: a strong convective updraft and downdraft above the surface windshift line, broader ascent over the cold front aloft, and convective ascent in generating cells aloft. The motion of the cold front and the rainbands in the figure is from left to right [After Matejka, Houze, and Hobbs (1978)]

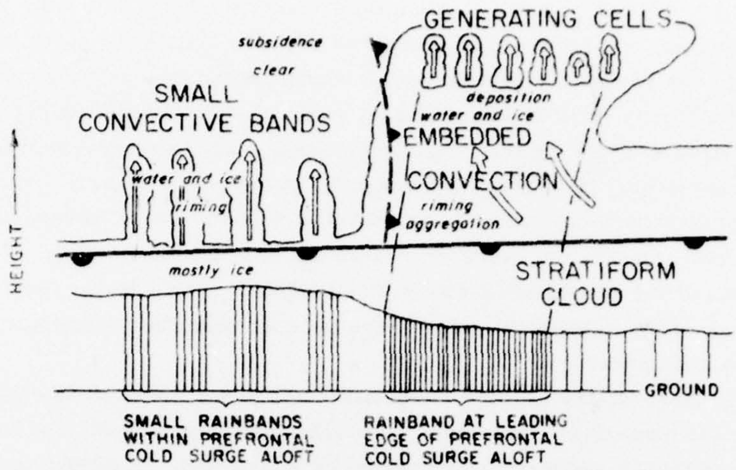

Figure 8d. Schematic Vertical Cross Section Through the Clouds Associated with a Surge of Cold Air Aloft, Ahead of an Occluded Front. A broken cold-frontal symbol indicates the leading edge of the mesoscale cold surge aloft. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds to the precipitation rate. Open arrows depict airflow in convective generating cells aloft and airflow ahead of and relative to the cold surge. The motion of the cold surge and the rainbands in the figure is from left to right [After Matejka, Houze and Hobbs (1978)]

Unfortunately, studies such as the University of Washington CYCLES project, from which the data for Table 5 and Figures 8(a) to 8(d) have been obtained, are rare. It is not possible at present, either to talk about an "average" or "typical" cloud system, or even to put bounds on the sizes, concentrations, and types of ice particles to be expected in various cloud systems.

7. MODELS OF CRYSTAL GROWTH

It is possible, by applying basic physical concepts and using large-scale computers, to derive mathematical models depicting the growth of ice crystals under various environmental conditions. Generally, these studies take either one of two approaches. First, like Chappel and Smith (described in Dyer and Kunkel[35]) one can assume a mixed-phase cloud with monodispersed crystal and droplet concentration, then compute step by step the changes in cloud supersaturation, droplet

35. Dyer, R.M. and Kunkel, B.A. (1978) A comparison of theoretical and experimental results in supercooled stratus dispersal, AFGL-TR-78-0193, AD A063 013.

growth and ice crystal growth. Assumptions must be made concerning the collection efficiencies, and the transition between unrimed and rimed particle growth. Such models are useful in determining the relative importance of the various physical parameters such as temperature, vertical velocity and liquid water content on the growth of ice crystals in a mixed cloud, but they are very difficult to apply to observations in the real atmosphere, as opposed to the cloud chamber.

Another approach is to assume an initial size spectrum, as Passarelli[36] has done with snow, and then to solve the resulting equations analytically to determine the evolution of the size spectra with either height or time. Here, too, assumptions must be made of physical parameters such as collection efficiency, temperature profile and updraft.

As yet, observations are neither detailed nor precise enough to evaluate properly either the numerical integration approach typified by Chapell and Smith or the statistical-analytical approach represented by Passarelli. In either case, juggling the values of the unknown parameters results in computations that approximate observations of the resulting gross parameters, such as precipitation rate. However, as yet such models cannot be used to predict ice crystal concentrations in particular instances.

8. CONCLUSIONS

This study represents a brief survey of the current state of the art of the microphysics of ice clouds. Many questions remain to be answered before the microwave engineer, aerodynamicist or atmospheric scientist can feel confident that the ice cloud environment of interest to him has been defined with sufficient accuracy and precision.

Among the unsolved problems is that of ice particle enhancement. Specifically, prediction of the multiplying factor between ice nuclei concentration and ice particle concentration requires answers to the following: (1) What are the mechanisms causing particle enhancement? (2) Under what circumstances does enhancement occur? (3) How does enhancement vary with time, temperature, geographic location and position within the storm?

Another unsolved problem is the growth of ice and snow by aggregation and deposition. Modeling of growth theories and testing of theoretical results against atmospheric data are necessary.

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36. Passarelli, R.E. Jr. (1978) The Evolution of Snow Size Spectra in Winter Storms, Tech. Note 52, Univ. of Chicago, Dept. of Geophysical Sci.

Ideally, the end result of research into the microphysics of ice clouds would be statistics, giving expected concentrations, sizes and crystal types as a function of air mass, cloud type, cloud location within a storm system, cloud age, location within the cloud, and geographic location and time of year. At present, there is no agreement as to which of the many factors influence the particle spectrum. As stated previously, spatial variations seem to be more important than time variations in cirrus and cirrostratus clouds[8] while the reverse is true in cumulus and cumulonimbus clouds.[21, 18] With the notable exception that the stratus clouds in the Arctic and Antarctic do not show the multiplication factor between ice nuclei and ice particles evidenced by stratus clouds in the temperate zones, the present scant observations do not seem to show any generalized, systematic variation in cloud particle spectra with geographic location.

This question must first be answered before any definitive handbook of the expected environment in ice clouds can be compiled: Which parameters are important in determining the microphysical structure of clouds?

9. RECOMMENDATIONS

In order to acquire the data necessary to advance our knowledge of ice cloud microphysics, several types of research programs are necessary. First, observations of crystal types, size spectra, and related parameters should be taken to provide an adequate base for the development of statistical summaries for immediate, as well as future Air Force use; second, theoretical models of ice and snow growth should be explored in detail and tested against observations taken in the atmosphere; third, systematic observations in which ice nuclei and ice particle spectra are measured periodically during the life of a cloud should be made, and analyses performed either to verify or refute the hypotheses advanced and to assess the role and relative importance of ice nuclei; and fourth, projects similar to those conducted at the University of Washington should be undertaken at various locations in order to investigate storms in detail and to provide information of geographical differences.

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